Development of an Earthmoving Machinery Autonomous Excavator Development Platform

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Abstract –
This paper presents the initial planning phase results of excavator automation in the SmartBooms research project funded by Business Finland. Automation control is a key factor for the earth construction industry. Automation of excavators enables increased productivity and accurate adjustment of the digging work process, especially in depth control, which results in cost reductions. For design and research of excavator automation, a development platform has been planned using an E85 Bobcat 8.5 t excavator equipped with modified hydraulics and controls. Simulation and software development was selected using Matlab Simulink Realtime Desktop with SimlabIO CAN bus communications and custom code, while additional software development is performed mainly with integration of the robotics simulation software V-rep and Matlab.

Keywords –
Excavator; Automation; Development Platform; Robotic;

1 Introduction

1.1 Development trends of automatic 3D control systems for construction machinery

Over the past few years, the construction machinery, mining, and forest industries have experienced particularly vigorous development in the field of work machines and directly integrated digital processes, and in automation. Finland is currently a pioneer in the world of information modeling and automation in earthworks. The control of earthmoving machinery is based on information models that provide the necessary information for control systems in machines.

Typical automatic 3D control systems at the machinery level are (Tab. 1) for example guidance (the driver moves the machine and manages the machining blade manually on the basis of computer display information); coordinating (the driver moves the machine and manages the machining blade manually with the help of inverse kinematics), guiding (the driver moves the machine and controls some of the movements of the machining blade manually when the system is running automatically on some movements), and autonomous (operating without a driver). In the Nordic countries in particular, guidance, coordinating, and guiding 3D control systems are already widely used in the control of earthmoving machinery.

Table 1. The levels of automation for earthmoving machinery.

Level	Name	Description of the activity
0	No automation	Human operates machine
1	Remote control	Human operates remotely machine
2	Guidance	Operator supported, the operator drives manually machine and blade using computer user-interface to BIM model
3	Coordinated	Tip control, the operator moves the machine and manages the tool blade manually with the help of inverse kinematics
4	Partial automation	Controlling, the operator moves the work machine and manages the part of the tool blade manually while the system drives automatically some of the movements
5	Autonomous	Machine can operate without human driver
6	Autonomous machine swarm	Autonomous operation of work machines, interactivity and collaboration of working machines

The level of automation also depends on the type of machine. In spreader-type machines such as graders, bulldozers, and asphalt spreaders, the control systems are already actively controlling automated movements. In boom-type machines, control is generally still at the guidance level, where the driver manually controls the boom based on the control information displayed by the system. To increase the automation level in control of machines, one of the basic problems and challenges is to take account of changes in the work environment efficiently and safely. Other machines, vehicles, and people may move into the working area of the machine, or the material to be cut or loaded in excavator work can move unpredictably. Automatic functions always require sensing and control values calculated by the computer. Verifying the condition and correctness of sensing and steering is closely related to the security review of autonomous movements.

An interesting algorithm toolbox and development platform has been introduced by Fraunhofer IOSB [1]. The purpose is to equip a variety of robotic systems with different autonomous capabilities relevant for their intended purpose with minimal adaptation effort.

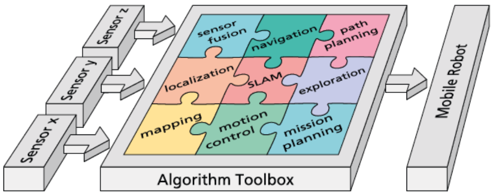

Figure 1. Fraunhofer Algorithm Toolbox for Autonomous Mobile Robots [1].

The puzzle modules of the Toolbox of Fraunhofer are mapping, localization, sensor fusion, motion control, SLAM, navigation, mission planning, exploration and path planning (Fig. 1).

1.2 Automatic control for Excavator

The excavator is a general-purpose machine on construction sites, with a high number of operating hours. The excavator has a lot of end-effectors such as buckets of different sizes, spikes, vibrators, and accessories for pipe installation, drilling, piling, stabilization, etc. The tasks are very versatile and challenging with guidance. The most typical infrastructure construction tasks are ground cutting, loading, material reception, and geometrically challenging ramp work.

The Robotics Institute at Carnegie Mellon University (USA) performed an interesting experiment with an autonomous excavator back in 1998 [2], while LUCIE by Lancaster University [3] is equally well known. The research group behind Carnagie Mellon created a model from the surrounding area and was able to find and fill a truck without the help of a human operator.

In recent years, Komatsu has been one of the most important technology drivers in the construction industry. Komatsu has already introduced an excavator control system. Novatron Ltd is currently marketing a guiding Xsite PRO system, which is the most integrated of commercial systems in the overall process of open information modeling (Open Infra BIM).

Figure 2. Commercial example: the Leica iCON iXE3 Copilot.

Figures 2 and 3 show the automation system of the Swiss Leica, where the guidance system has integrated automatic control of the level of cut of the excavator bucket, based on an angle readings by the machine control model. The Trimble Earthworks system automatically controls the lifting of the main boom according to the model, otherwise the operator manually drives the machine in the guidance model.

Figure 3 Testing the Leica machine automation system at Destia Ltd construction site in Vaala, Finland.

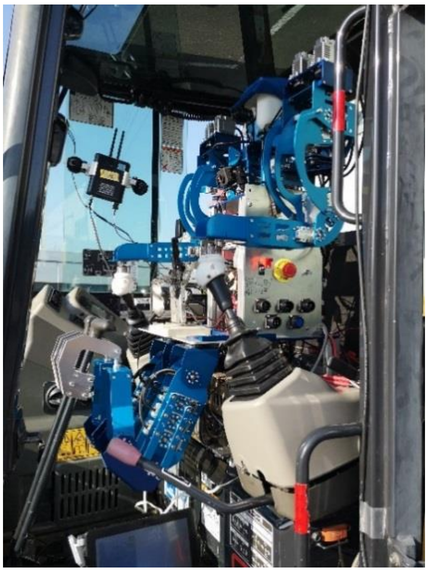

Figure 4. Research project in Japan by Kanamoto Ltd, on a movable humanoid remote robot for remote control.

Figure 5. Control and pilot station for more realistic remote operations.

It is particularly interesting to study and monitor the development of guidance technology in Japan, which is constantly affected by landslides due to earthquakes, typhoons, and sensitive earth material. These conditions are dangerous for workers, which is why Japan has developed and switched to a wide range of remote-controlled earthmoving machinery (Figures 4 and 5). In this case, the operators sit at a safe distance from the work site, in cabins from which they can control the heavy machinery using video connections and machine control systems. Some companies use a human robot in these systems to repeat as accurately as possible the drive movements made by the human operator in a safe cabin. However, Japan is lagging behind northern Europe in the use of information modeling based automation.

The self-propelled or self-contained excavator has been a research and development goal for quite some time. Various test systems have been tested. For example, the excavator introduced by Carnegie Mellon University in 1998 [2] was able to fill a truck platform without driver assistance, based on laser scanning. Automated excavators for construction sites have still not become mainstream, but development activities are now properly ongoing.

1.3 Aim of the research

The aim of the research and paper was to develop and experiment the new robotic development platform to the University of Oulu as well as to introduce the first results how to apply the platform for practical developments and experiments.

2 Automated Excavator Development Platform and the Experiments

The University of Oulu is developing an autonomous excavator in a SmartBooms research project funded by Business Finland. The aim of the SmartBooms project is to research and develop a new, continuously adaptable and automated control method for the boom of working machines through:

1. Developing automated control of the movements of machine and booms.
2. Use of different information models and real-time situation updating by continuous surveying.
3. Modular development enabling wide and versatile development of control applications in the earthmoving, forest, and mining industry, and installation of the control systems at the early manufacturing phase in the machinery factories
4. Applicability to product development of smart boom control systems for earthmoving, forest, and mining working machines.

2.1 Excavator and equipment

Figures 6 and 7 show the Bobcat E85 (8.5 t), which was chosen as the excavator machine by public tender. This excavator size was chosen to fit general construction sites, so it can be tested in a wide range of tasks, including road construction. It was decided to steer away from larger excavators, to make maintenance and handling easy, while smaller excavators are not well suited to general-purpose digging and there is too little room for fitting the components and sensors needed. The machine needed to undergo a complete overhaul of the hydraulic systems, where valves were retrofitted for precise electrical control. For hydraulic control, a separate control unit was installed. To equip the excavator with a sight, a laser measuring device was installed onto the stick boom of the machine.

Figure 6. The University of Oulu's Smart Bobcat E85 Excavator.

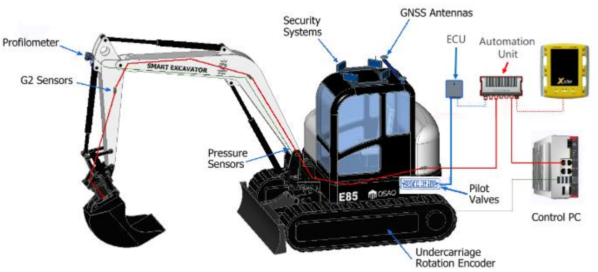

Figure 7. Components of the University of Oulu's Smart Bobcat E85 Excavator.

The basis of the sensory system are newly developed Novatron IMU G2 sensors, which can work up to 200Hz frequency. They provide accurate and precise positioning of the excavator which is good enough for automatic movements. Novatron's G2-type sensors have CAN bus-interfaced sensors. Use of CAN bus decreases the need for wiring and all sensors can be set at the same bus. Sensing accuracies and characteristics of the sensors were tested with the KUKA industrial robot (Figure 8). Dynamic and static features of previous versions of the Novatron sensors were also tested at the University of Oulu [4]. The new G2 sensors are significantly more accurate and reliable than the previous versions of Novatron sensors used widely in earthmoving work.

CAN bus is widely used in the automotive industry and various other industries. It is a low-cost device with less wiring, it works in various electrical environments, and it uses priority according to node ID [5].

Figure 8. G2 sensor testing using a KUKA robot manipulator

For global coordinates, a Trimble GNSS system is used in combination with an Xsite machine control system to provide location data. Communication between Xsite and hydraulic control is by CAN bus, while communication between machine and main level development pc is by both CAN bus and Ethernet proxy.

For safety reasons, it was decided to implement a camera system, most likely in the roof of the excavator. Laser profilometers and stereo sensors are currently selected to fit the excavator to provide data for both security and path planning. In the experiments, a new miniaturized 256x8 pixels line laser profilometer developed at University of Oulu was used.

2.2 Simulation environment

Virtual prototyping and code development testing were first intended to be performed in Matlab only, but it quickly emerged that this was not a reasonable approach, even using a Virtual Reality Toolbox. The Msc.Adams that we have successfully used previously for this purpose [6, 7, 8] was too laborious, lacked programming methods, and was too restricted to be selected. The game engine approach we have used previously in one case [9] is well suited to this task, but is quite a human resource-intensive option. After testing multiple general- and special-purpose virtual simulators, we selected the V-rep robotic simulation tool [10]. The main reasons were a) ease of use, b) light enough to run in normal laptop, and c) reasonable Matlab integration.

For non-commercial and educational use, Coppelia Robotics offers an educational license for The Virtual Robot Experimentation Platform. V-rep is a practical tool for the purpose, since it has many built-in actuators and sensors that are easily modified with scripts. That is why it requires less effort to build a functional environment compared with general tools such as Msc.Adams and Simulink. Model building in the V-rep scene editor is intuitive. Other specialist systems lack significant features such as mesh manipulation, simulation video, and multiple default physics engines. V-rep also has a wide library of miscellaneous robots, vehicles, and objects.

V-rep was chosen as a platform for the prototyping and testing of controls, and sensing of the automated excavator. Simulation parameters and movement are controlled through remote-API with external applications such as Matlab, where an inverse kinematics model and functions to operate actuators and to manipulate sensing data will be built.

With default simulation settings, V-rep simulates the tested scene (Figure 9), which simplifies the dynamic model, as represented in Figure 10, with execution times of around 40 ms for non-threaded scripts and of 10 ms for dynamic handling calculations. Because the calculation time increment is 50 ms, the calculations are somewhat faster than real time and the simulation video is rendered at around 24 frames per second. For the scene shown in Figure 10, one minute of simulation took 55 seconds running in the researcher's basic laptop. Simulation has an option for the lower accuracy and lighter calculations, as well as the customized time increment.

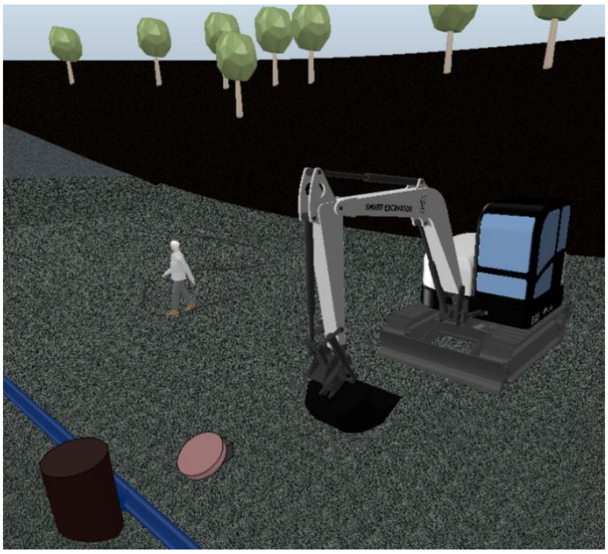

Figure 9. Test scene to study performance of the simulation software.

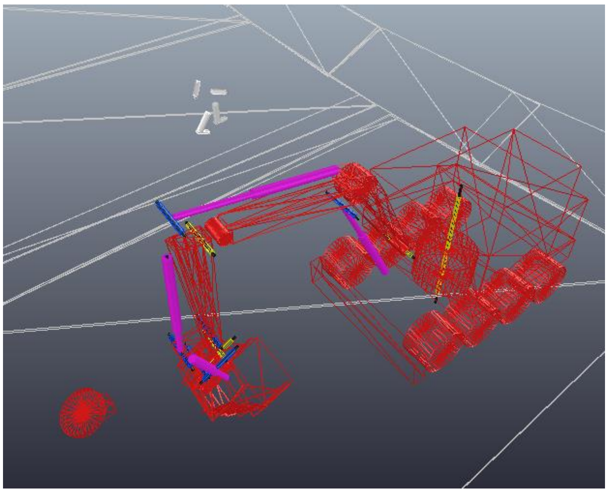

Figure 10. Simplified dynamic model for simulations.

A series of tests were performed using the robotic development platform. In the paper some observations from sensor calibrations, the use of the industrial robot as a reference model for the generation of digging trajectories i.e. control models, the first experiences of V-rep robotic development software as well as some test results of the new type of laser profilometer are reported.

3 Results

In the experiments with KUKA industrial robot, three IMU G2 sensors attached to the robot were used for real-time accurate capturing of boom and bucket movements. Actually, a kinematic sensor calibration of the G2 sensors was successfully performed using the driving paths of the robot as references. The robot was programmed to mimic real excavators digging movements to acquire data of G2 sensors repeatability, angle accuracies and effects of acceleration to the sensors data. Valuable detailed data of sensors abilities were gathered during robot measurements and will be reported later.

The first experiences of the V-rep robotic development software quite positive. The software has a good user-interface with a support of versatile robotic subroutine library, and the programming work was found to be relatively easy to execute. The accuracy and complexity of model details can slow down the real-time calculation of the program.

Experimental field tests and obtained results showed the suitability of the laser profilometer for surface changes monitoring and 3D visualization of a surface from the excavator (Fig. 11). The applied method seems offer sufficient measurement accuracy in relation to the measurement range in work site. As the main advantages of the method the monitoring does not require expensive measuring equipment. Typical measurement materials and targets on earth construction sites seems to have sufficient reflectivity, color, and brightness of the object surfaces to be captured by the measurement system.

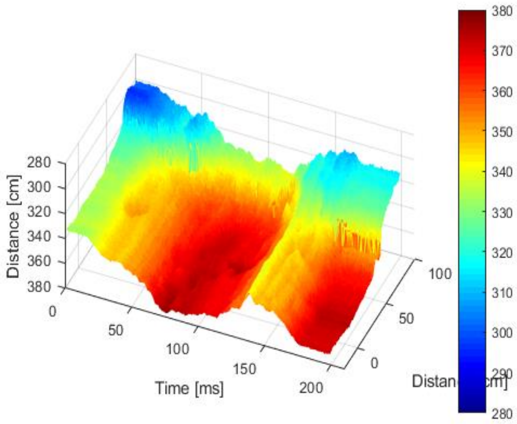

Figure 11. A pit measured by the laser profilometer from the boom of Bobcat excavator.

4 Conclusions

The SmartBooms project has created a simulation test environment and robotic development platform into University of Oulu for the development of autonomous excavation equipment. The simulation environment was a powerful tool for safely testing new concept and control algorithms. The platform utilizes also the selection of newest sensor systems with IMU G2 sensors and a solid state laser measurement system developed at University of Oulu.

The main software chosen for development was Matlab Simulink Realtime with SimlabIO integration to CAN. The main platform software is supported by many different tools, with V-rep used extensively. The physical excavator chosen through public tender is a medium-sized Bobcat E85 equipped with a Novatron Xsite machine control system.

The puzzle modules of the Toolbox of University of Oulu are so far 1) open information modelling, 2) positioning in accurate coordinate system, 3) sensor fusion, 4) motion control for machine rotation and movements of booms and bucket, 5) machine transition and navigation, 6) mission planning and work task creation, 7) path generation and 8) safety assurance.

Our goal in future work is to produce a fully autonomous excavator operating on an earth construction/excavation site according to the parameters given by the designer. In addition, the excavator algorithm must prevent the excavator from undesired and possibly destructive movements. A self-moving machine must always know what to do. The most important facilitator of autonomous control and machine learning, *i.e.* "machine intelligence", is integration into the information modeling process used by the Infra industry.

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